Tracking Subpixel-Scale Sastrugi With Advanced Land Imager

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***Abstract*—High radiometric resolution imagery from the Advanced Land Imager (ALI) can detect the spatial reflectance variations associated with sastrugi (snow dunes) on ice sheets. This is shown, in theory, by considering the appropriate SNR ratio of ALI as compared with eight-bit optical sensors and, in practice, with mutlitemporal ALI imagery. Comparison of ALI imagery spanning 7.5 months also shows that the reflectance pattern associated with sastrugi can persist over this interval offering the potential of their use for measuring ice sheet velocity in uncrevassed regions.**

***Index Terms*—Ice sheets, image sensors.**

I. Introduction

CAPTURING the detailed topography of ice sheets is a challenge for orbiting optical imagers. The bright surface and nearly flat topography makes the range of radiances in the field of view very small. Often much of this topographic detail is hidden from view, at or below the noise level of the imaging sensor.

Ultimately, the issue reduces to one of sensor performance, i.e., SNR. Numerous long-running series of satellite imagers confined radiance quantization to eight bits. Increased communication bandwidths with satellite remote sensors has opened the door for recent optical imagers to include finer radiometric resolution. Quantizing radiance over more than eight bits has allowed the exploration of details of ice sheets with satellite optical imagery. This paper illustrates that with the 12-bit quantization of the Advanced Land Imager (ALI), it is possible to detect the very subtle variations of surface reflectance associated with the presence of sastrugi (snow dunes) on the ice sheet surface. This is achievable even though the sastrugi individually are of a physical size too small to be resolved by the sensor.

It is also shown that the pattern resulting from sastrugi is unique enough that separate images of the same area can be correlated by this pattern. By also establishing that these sastrugi fields can persist over many months, the potential for measuring the surface velocity of the ice sheet by tracking the motion of sastrugi fields is identified. This capability would expand the uses of optical imagery for ice sheet research and afford glaciologists the ability to measure ice motion in regions that previously required ground occupation or interferometric radar techniques.

Manuscript received May 2, 2002; revised October 28, 2002. This work was supported by the National Aeronautics and Space Administration Earth Science Enterprise while the author was a member of the Earth Observing 1 Science Validation Team.

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Digital Object Identifier 10.1109/TGRS.2003.812902

Fig. 1. IKONOS image of a portion of the Bindschadler Ice Stream, Antarctica, collected on February 9, 2001. Image is a 1 km $\times$ 1 km portion of the collected scene. Visible sastrugi are elongated along the predominant wind direction, which here is from upper right to lower left.

II. Data

Sastrugi are snow dunes formed by wind deposition and erosion of the ice sheet surface [1]. They are pervasive across the ice sheet where snow and wind are in ample supply. Their sculpted shapes are typically saw-toothed with the steeper eroded face on the upwind side and the longer tail pointing downwind. Dimensions of a single sastrugi are typically a meter to a few meters in the horizontal and a few tens of centimeters in the vertical, depending on wind strength, temperature, and snow hardness. Occasionally, much larger sastrugi have been noted, but they are believed to be rare or limited in regional extent.

An IKONOS image produced by Space Imaging was used as proxy ground truth in this study. Panchromatic data from this sensor are supplied to the user at 1-m pixel resolution with an 11-bit linear quantization of the full range of expected solar radiances over the 400–1000-nm spectral range of the band. With this spatial resolution, individual sastrugi can be identified. Fig. 1 is a 1-km^2 subset of an IKONOS image showing a field of sastrugi. The prevailing wind direction, inferred from the general orientation of the long axes of sastrugi, is from the upper right to the lower left. The full 11 km $\times$ 11 km IKONOS image (center coordinates: 81.08°S, 140.5°W) was collected of

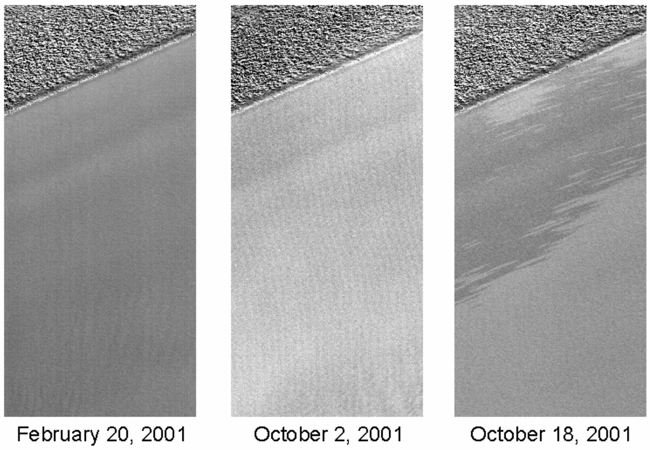

Fig. 2. Three images of the edge of the Bindschadler Ice Stream collected on February 20, 2001, October 2, 2001, and October 18, 2001 by ALI. Data shown are 5.6 km $\times$ 9.6 km subsets of the full dataset cropped to be coincident in space. The heavily crevassed margin of the ice stream appears in the upper left of each image. Sastrugi-covered slow-moving ice dominates each image.

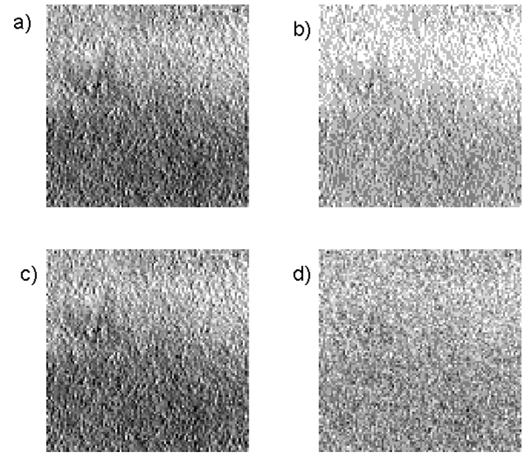

Fig. 3. Simulated images based on the 1-m 11-bit IKONOS image of Fig. 1. (a) Ten-meter spatial average to simulate an ALI panchromatic image. (b) Averaging of pixel brightnesses in (a) by a factor of eight to simulate an eight-bit sensor such as Landsat-7 ETM+. (c) Image (a) after the addition of ± 1 DN noise. (d) Image (b) after the addition of ± 1 DN noise.

a portion of the Bindschadler Ice Stream in West Antarctica on February 9, 2001.

ALI is a new design of optical imager and part of the National Aeronautics and Space Administration Earth New Millennium Program (*http://eo1.gsfc.nasa.gov/*). Carried onboard the Earth Observing 1 satellite, ALI's panchromatic band quantizes the full range of expected solar radiances over 12 bits between 480–690 nm, at a spatial resolution of 10 m. Data were collected in four groundtrack-parallel strips, each approximately 10 km wide. For this study, three images were used, each collected of the edge of the Bindschadler Ice Stream including a portion of the fast-moving ice stream and a larger portion of the slow-moving ridge south of the ice stream (Fig. 2). Dates of the images are February 20, October 2, and October 18, 2001, and each was collected using a target location of 80.8°S, 145.6°W. Sun elevations and azimuths are 9.8°, 3.9°, and 9.9° above the horizon, respectively, and 96.4°, 90.1°, and 90.1° from north, respectively. While the sun azimuth changes little for images from the imager's sun-synchronous orbit, the sun elevation was changing rapidly in October. By coincidence, the February 20 and October 18 images were almost equidistant from the winter solstice and, thus, have nearly identical solar elevations.

The edge of the ice stream strikes diagonally across the upper part of each image in Fig. 2. The heavily crevassed margin of the ice stream is above this boundary, while below the boundary the ice sheet is composed of a very slow moving ridge whose surface is covered with sastrugi. All three ALI images were cropped from wider data strips to capture their common area and avoid mosaicing adjacent data strips. Coregistration was based on a single set of unique features at the edge of the ice stream. No attempt was made to balance the enhancements of each image. Thin clouds appear in the lower portion of the February 20 image and possibly the October 2 image. On the October 18 image, the large area of lower reflectance on the ridge is neither cloud nor cloud shadow, but the result of a local wind event that smoothed the surface on the fine scale, creating a more specularly reflecting surface. This phenomenon occurs frequently on ice sheets and is seen in imagery because the data are often strongly enhanced. The change in reflectance typically is less than 1%.

IV. Conclusion

Sufficient radiometric resolution, such as provided by ALI, makes it possible to recognize and track fields of sastrugi even though individual sastrugi cannot be resolved. This leads to a tracking technique very much like speckle-tracking with radar imagery [7]; however, with radar the scatters can be beneath the surface as well as on the surface. Optical imagery is not sensitive to subsurface conditions, so the requirements are more stringent.

The finding that some sastrugi are persistent enough in this test area to produce a recognizable pattern of lighter and darker pixels in images separated by many months is surprising, yet the tests performed here confirm this as fact. This study also was able to demonstrate that neither the variation of sun angle and azimuth nor the presence of regions of slightly altered surface reflectance prevented correlation. Further testing of the persistence and recognition of sastrugi fields in other locations and for a wider variation of illumination and surface conditions is required before this result can be considered a robust tool for measuring surface motion of ice sheets.